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The opinions expressed by authors and contributors to discussions are those of the individuals concerned and are not necessarily those of the Society

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The Calculation of Illumination in Practical Lighting Design

By H. D. EINHORN, Dr.-Ing., Ph.D., A.M.I.E.E., M.(S.A.)I.E.E. (*Fellow*)

Summary

Practical design calculations must be simple and high accuracy is rarely required. The widely used lumen-method is becoming increasingly dependable; local lighting methods are nevertheless indispensable. The applicability of the point source concept is discussed, and the principles of line source calculations using the sector flux concept are briefly given. An example shows the combined use of point and line source methods. Flux relations are summarized.

(1) Introduction

Good lighting should fulfil two aims; it should be functional and aesthetically satisfying. To achieve this the designer may draw on his past experience, he may exercise his artistic taste and he may carry out lighting calculations. Some designers are strongly biased toward the intuitive approach and spurn calculations as unnecessary, and not worth their time. Others are convinced that an application of fundamental physical and biological knowledge to lighting design is worth while, and appreciate the value of quantitative assessment; they may nevertheless be appalled by the thickness of some admirable books on lighting calculations, while aware of the uncertainty of some of the data assumed. Considering the controversial choice of illumination levels, their spectacular growth over the years, and the wide divergence between national codes[1, 2] one may ask: is it worth while spending time on calculating illumination values? The answer is that a neglect of quantitative design may lead to installations where even the most modest code value is not reached; but on the other hand computations rarely need be accurate.

Practical calculation methods should therefore be simple and rapid, and approximations are often justified in place of exact formulations, which in many lighting design problems would be unpleasantly complex and tedious. The scientific designer should understand the limits of approximations, and know whether a simple formula can be used safely in any particular case. It will be the object of this paper to review some simple design calculations and to examine their limitations and the accuracy achieved.

(2) Accuracy

The accuracy required varies very much with the aim. The wide variations of code figures seem to indicate a very wide tolerance. This is quite true, if one merely wants to calculate the illumination on one's own dining room table. But when comparing different proposals or tenders for a particular job—which differ in lay-out, type of fitting, type of lamp perhaps and certainly in cost—a higher accuracy becomes desirable, commensurate with the accuracy of practical check measurements. For luminance calculations or for assessing uniformity the accuracy required may also be higher than for stating average values, since the human eye is more sensitive to contrast than to absolute level. The CIE proposal[4] that one should aim at *five per cent* accuracy in practical design seems to be reasonable, although estimates to a still lower degree of accuracy are often quite worth while and are superior to mere guessing.

(3) Lumen Method

The 'lumen-method' proposed by Harrison and Anderson forty years ago is the computing aid most commonly used by the illuminating engineer. This determines for a room the total lamp lumens (F_l) which will give a desired average illumination (E_{av}) over a certain working area (A); a utilization factor (K_u), dependent on room shape and colours and on type of fittings, is introduced, as well as a maintenance factor (MF) to allow for light depreciation.

$$F_l = E_{av}A/(K_u MF) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

The most controversial factor in this simple equation is the illumination level E_{av}. It is a matter of choice, and reference is usually made to national codes,[1, 2] of which the wide variation in different countries has been mentioned. To what precision can one ascertain the other factors?

The maintenance factor requires some guessing. Even if the use of average-through-life lamp-lumens eliminates some of the differences between lamp types, the often unknown character of atmosphere and future maintenance routine introduces a good

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deal of speculation. The traditional 0·8 value is little better than a safety factor or rather a factor of ignorance; relatively recent work by Wittig,[8, 14] which brought out clearly the appreciable difference between direct and indirect lighting, allows a more subtle assessment.

One should expect less uncertainty in the assessment of utilization factors, which were originally determined experimentally and in the last few years have been made a subject of thorough theoretical analysis* (started by the researches of Jones and Neidhart). Yet discrepancies can be found in tables published by reputable authorities.[2, 3] On closer analysis some can be traced to different assumed light-output ratios of fittings, American figures usually being higher than English ones. But when comparing older empirical data[3] with newer calculated data,[2] corrected for differences in light output ratio as shown in Table 1, it will be seen that the calculated data are higher than the empirical figures, especially in large rooms.† They are probably more dependable than the older figures, although the statement 'there is no reason to question their accuracy'[8] is perhaps a little bold, considering that most calculations are simplified by some assumptions or approximations; for instance luminance variations on walls are neglected, and differences between longitudinal and transverse lay-outs of fluorescent fittings have not been mentioned so far in published tables.‡ There is experimental support[7] for the higher theoretical figures, and although further measurements with cosine-corrected photocells would be desirable, the work proceeding at present on an international scale promises a more dependable basis of the lumen method.

Table 1

Comparison of Utilization Factors

Type	Room	$\varrho_c = \cdot 7$; $\varrho_w = \cdot 5$		$\varrho_c = \cdot 5$; $\varrho_w = \cdot 3$	
		B	*A*	*B*	*A*
Direct 0 / 70	S	·33	*·34*	·28	*·30*
	M	·50	*·54*	·46	*·49*
	L	·61	*·70*	·57	*·66*
General 45 / 35	S	·26	*·28*	·21	*·23*
	M	·41	*·45*	·35	*·36*
	L	·52	*·62*	·44	*·51*
Indirect 75 / 0	S	·15	*·15*	·08	*·08*
	M	·27	*·27*	·16	*·16*
	L	·37	*·44*	·22	*·31*

Room Sizes S: 16′×10′; M: 35′×20′; L: 170′×50′
Room Height 8′ above working plane; 10′ 9″ above floor
Reference B=B.L.C. 1960[3]; A=IES(N.Y.) 1960[2]
All data are corrected for differing light output ratios.

The A figures are based on calculation, the B figures are empirical. Numbers in first column refer to the percentage upward and downward flux assumed.

* See bibliography in [2, 6, 14].
† See also Narracott [6].

It is doubtful whether many designers went back to the flux component method on which utilization factor tables were originally based, or would be prepared to use the newer zonal method[5] in its basic form. The author agrees with the view[6] that K_U-tables of more or less the traditional pattern will have to be derived by the new method, and that standard tables are required, although manufacturers can help greatly by publishing tables for their own fittings. The usual statement of the light output ratios can be used for correcting standard values. Sometimes, e.g. when comparing inside silvered lamps with fittings containing GLS lamps, it might be useful to split the utilization factor into two components, 'light output ratio' to allow for losses in fittings and 'utilance' to allow for absorption in ceiling and walls.

More important than minor inaccuracies in the lumen method are doubts about the significance of an *average* illumination level. Should we rather aim at determining *minimum* illumination values? This would in most cases be more difficult, and is not necessary if a few precautions are taken:

(i) Maximum spacing/height ratios should be kept within reasonable limits.
(ii) Attention should be paid to positions near walls, especially to areas beyond or below the end of long rows of fluorescent fittings.[2, 14]
(iii) Attention should be paid to special positions where local or localized lighting is wanted.

For these purposes a competent lighting designer requires point-by-point methods. They can be divided into:

(*a*) point source calculations, which are quite simple and familiar,
(*b*) line source calculations, which are still simpler although not as widely appreciated as they deserve to be,
(*c*) general extended source calculations, which are usually too complex and cumbersome for everyday illumination design.

(4) Point Source Calculations

The inverse square law is elementary in principle. It pertains only to a single point source; a miscon-

‡ See also Walsh, Lynes [6].

ception of this limitation has occasionally led to the use of pendants where ceiling mounted fittings would be more appropriate. On the other hand, conscientious designers and laboratory engineers often hesitate in applying the inverse square law when it would be quite within the accuracy of the task in hand.

An estimate of the possible error (or a correction term) can be obtained by calculating the deviation from the inverse square law, for which a close approximation can usually be obtained in the form

$$E=(I/R^2)(1+c\lambda^2) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where E is the illumination on a surface, at distance R, facing a light source which has an intensity I and a largest extension L, c is a constant and $\lambda=L/R$. The deviation $c\lambda^2$ is the first term of a series expansion, and is as a rule negative for a 'wide' source but positive for a 'deep' source. 'Wide' means here extension of the source perpendicular to the I-direction; 'deep' means extension in the I-direction, and R is measured from the midpoint of the source.

Table 2 and Fig. 1 give an idea of possible errors by stating for some sources of simple shape the fractional deviation from the inverse square law over a range of distances, and the minimum distance at which the inverse square law can be applied without exceeding a certain error limit.

A combination of two point sources, to which a two-arm chandelier approximates, represents the extreme case. A luminous ring, e.g. a 'circline' lamp, behaves like the spheres in case (*b*). The deviation is small for sources extended both in width and depth, such as a fluorescent lamp at an angle of 30°; in the classical case of a diffusing sphere the inverse square law applies rigorously.

Table 2

Deviation from Inverse Square Law

Type of Source (largest extension $L=\lambda R$)	Fractional Deviation at distance R	Minimum R/L for deviation within 1%	2%	5%
(*a*) Two small discs displaced sideways by L	$-\frac{1}{2}\lambda^2$	7	5	3·2
(*b*) Two uniform spheres displaced sideways by L (also toroid)	$-\frac{1}{8}\lambda^2$	6	4·3	2·7
(*c*) Flat disc, also concave round reflector	$-\frac{1}{4}\lambda^2$	5	3·5	2·2
(*d*) Thin cylinder (normal to direction of R)				
(i) Fluorescent lamp	$-0{\cdot}18\lambda^2$	4·3	3	2
(ii) Uniformly diffusing	$-\frac{1}{6}\lambda^2$	4	3	1·8
(*e*) Thin diffusing cylinder at 30° from normal	$-0{\cdot}04\lambda^4$	1·4	1·2	0·9
(*f*) Diffusing sphere	0	—	—	—
(*g*) Thin cylinder at 45°				
(i) Uniformly diffusing	$+\frac{1}{8}\lambda^2$	4	3	1·8
(ii) Fluorescent lamp	$+0{\cdot}23\lambda^2$	5	3·4	2·2
(*h*) Two points displaced in depth by L	$+\frac{1}{4}\lambda^2$	9	6	4

NOTES: Distance R is always measured from centre of source, or from midpoint in (*a*), (*b*), (*h*).
For (*a*), (*c*), (d_{11}), (*e*), (*f*), (g_1) uniform diffusion is assumed.
To (*e*): The λ^2 term disappears for 30° angle.
The term $-0{\cdot}04\ \lambda^4$ determines the order of the deviation.
To (*f*): A perfectly diffusing sphere obeys the inverse square law rigorously.

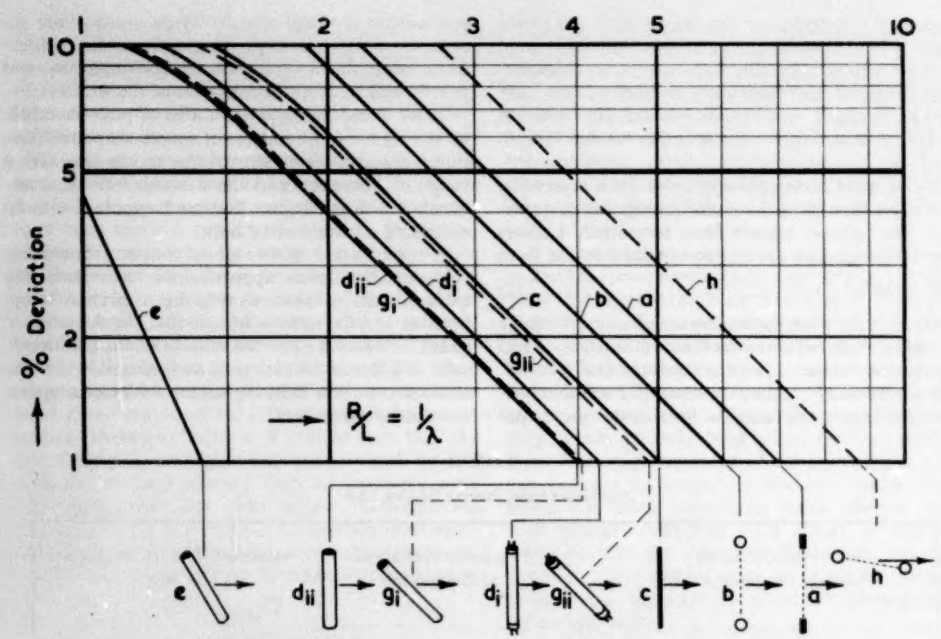

Fig. 1. Percent deviation from inverse square law as a function of relative distance from source. R = distance; L = largest extension of source. Full lines: negative correction. Broken lines: positive correction. Lines are identified by symbols corresponding to those in Table 2 and by sketches below graph.

For practical estimating, fluorescent fittings can be dealt with as point sources at distances above two lamp lengths; for closer distance or greater accuracy the illumination in directions normal to the lamp axis can be calculated as [15]

$$E=(I/R^2)(1-0{\cdot}18\lambda^2+0{\cdot}042\lambda^4) \quad \ldots\ldots\ldots \quad (2a)$$

For a dispersive industrial reflector containing an incandescent lamp, in the direction of its principal axis the illumination deviates from the inverse square law by less than 1 per cent if the distance is measured from a point about one-third way between lamp and plane of reflector edge, say from the bulb surface instead of filament centre.

(5) Line Source Calculations

Point by point calculations for linear lay-outs have become important with the increased use of fluorescent lamps. Although a single fluorescent fitting is more like a point source than a line source at the usual distances, in many modern installations fluorescent fittings are mounted in rows or in coves and cornices. They can then be considered as long line sources and the designer will find the sect-or flux concept useful. It was first proposed in 1951[9] and further elucidated subsequently.[10–14]

(*a*) The sector flux (J) is a directional quantity pertaining to a line source, analogous to the intensity concept for a point source.

(*b*) Just as a non-uniform point source has an infinite number of intensities, a line source, unless uniform, has an infinite number of sector fluxes; the variation of sector flux with direction can be described by a polar curve, perpendicular to the axis of the source (see Fig. 2).

(*c*) The sector flux is the numerator in the inverse first power law for a long line source: $E=J/R$. If E is in lumens per square foot and R in feet, J is in lumens per foot per radian (lm/ft. r).* In this simplest form the surface lighted must face the source and be parallel with its axis.

(*d*) If the surface is parallel with the source, but tilted away from it in a plane normal to the source axis by an angle β (see Fig. 2), the relation obtained is:

$$E=\frac{J}{R}\cos\beta=\frac{JH}{H^2+Z^2} \quad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

* If E is in lux and R in m, J is in lm/m.r

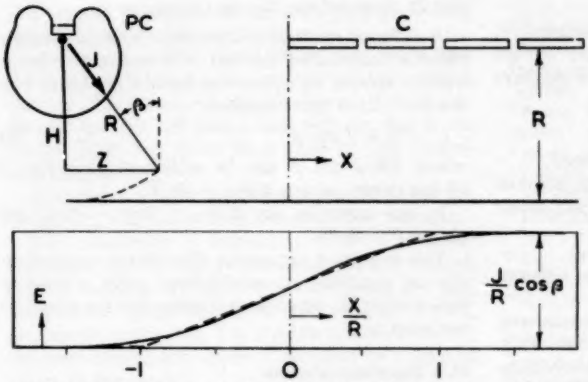

Fig. 2. Sector flux relations.
Left top: polar curve and normal lay-out with dimensions for equation 3.
Right and below: longitudinal lay-out with end-effect correction curves. Full line gives curve for fluorescent lamp; broken line corresponds to equation 4.

If the object surface is not parallel with the source, the calculation is more complex, but curves for object surfaces normal to the source axis, such as an end wall in a room with longitudinal rows of lamps, have been published.[9, 10, 13]

(*e*) No real line source is infinite, and if the object surface is near the end of the line (say if $X<R$ in Fig. 2) an end correction should be made. By assuming a linear reduction of illumination from unity at $X/R=1$ to zero at $X/R=-1$ (the negative sign referring to regions beyond the end of the source) a simple end-correction factor is obtained:

$$f_e=\tfrac{1}{2}(1+X/R) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

which yields results within ± 8 per cent for most fluorescent fittings.[14] A better accuracy can be obtained by means of a correction graph.[9, 10, 11, 13]

(*f*) Sector flux values can be assessed from lamp flux or from fitting intensities in the normal plane. If fittings are spaced at pitch C (Fig. 2) and contain n lamps each of F lumens, and if m is the reflector magnification, i.e. the ratio of fitting intensity/bare-lamps intensity, then

$$J=mnF/2\pi C \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

If the fitting intensity I_f is known, then

$$J=(J_o/I_o)(I_f/C) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

where the J_o/I_o-factor varies between 1·1 for deep louvers and 1·6 for matt reflectors.[10, 11, 13] If a polar curve and the net fitting lumens are known, J can be determined accurately.[11]

Typical sector flux values[11, 14] for continuous rows of bare lamps show that convenient design steps are obtainable if there is a choice between 4 ft 40w and 5 ft 80w lamps, or correspondingly loaded 8 ft lamp types:

Single 40w	:	100 lm/ft r	(60 lm/ft r)
Single 80w	:	150 lm/ft r	(90 lm/ft r)
Twin 40w	:	200 lm/ft r	(120 lm/ft r)
Twin 80w	:	300 lm/ft r, etc.	(180 lm/ft r)

The first column of figures are initial (100 hour) values for bare high efficiency lamps, mounted end-to-end. The second figures (in brackets) are average-through-life values for bare de luxe lamps. Intermediate values are obtainable by leaving gaps between ends.

(6) Practical Example

A simple example from the author's practice will demonstrate the joint application of sector flux and intensity concepts.

A 50 ft×5 ft wood inspection table had to be lighted to at least 30 lm/ft² maintained. Inspectors stood along one long side of the table and all specular reflection from horizontal boards had to be eliminated; light had therefore to come from behind the inspectors. To avoid sharp shadows, it was decided to install a continuous row of 'direct' type fluorescent industrial reflectors 5 feet above the edge of the table (see Fig. 3). Lamp rating and number had to be determined.

The use of the lumen-method in a case like this would be quite inappropriate, since the effective area of the working plane is ill defined and reflected light from the ceiling, while desirable for general comfort, would add only a small amount to the local illumination.

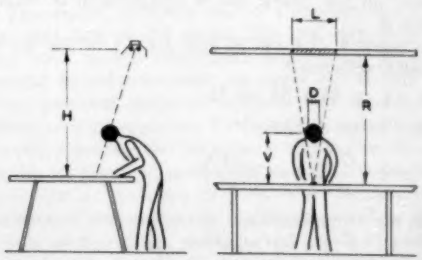

Fig. 3. Linear lay-out and head-shadow effect.

(6.1) Unobstructed conditions

The calculation for unobstructed conditions, i.e. ignoring the inspector's shadow, is very simple indeed. From equation (3), for a reference position of 1 ft 6 in. from the table's edge:

$$E_u = 5J/(5^2+1\cdot5^2) = J/5\cdot5 \text{ lm/ft}^2.$$

Two allowances, however, have to be made:

(i) for light depreciation—a maintenance factor of 0·85 was assumed for fair conditions and direct lighting;[8, 14]

(ii) for the shadow of the inspector's head.

The latter can be estimated by two quite different methods, which merit detailed treatment.

Ignoring this shadow problem for the moment, the desired sector flux would be: $J_u = 5\cdot5\times30/\cdot85 =$ 195 lm/ft r. A single row of 5 ft 80w 'Colour Matching' lamps in reflectors, designed to double the sector flux in the desired direction, would meet this requirement: $J = 2\times3040/2\pi5 \div 195$ lm/ft r (from equation 5).

(6.2) Effect of worker's shadow

(6.2.1) *Point Source Correction*

One can reason that the inspector's head will obstruct a certain part (L) of the line source, and the illumination (E_o) which would have been obtained from the section L is to be deducted from the unobstructed illumination value (E_u).

Referring to Fig. 3, the obstructed section can be treated as a point source of intensity LI_o, where I_o is the source intensity per foot run, if $V > 2D$. Hence $E_o = (LI_o/R^2)\cos\beta$.

Substituting the ratio D/V for L/R, where D is the diameter and V the 'viewing' distance of the head, and remembering that $E_u = (J/R)\cos\beta$, we obtain $E_o/E_u = (D/V)(I_o/J)$, from which a 'shadow factor' can be formulated:

$$f_s = 1 - \frac{D}{V}\frac{I_o}{J} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

It can be seen that the *relative* reduction thus expressed depends only on the size and distance of the obstruction (in this case the head), and the 'J/I_o factor' of the fitting, but is independent of its distance R.

Assuming $D/V = 0\cdot34$ and $J/I_o = 1\cdot55$ for an industrial reflector[10]

$$f_s = 1 - 0\cdot34/1\cdot55 = 0\cdot78$$

For better accuracy[15]

$$f'_s = 1 - \frac{D}{V}\frac{I_o}{J}\left(1 - \cdot18\frac{D^2}{V^2}\right) \quad \ldots\ldots\ldots\ldots\ldots (8)$$

In the example chosen this refinement is unnecessary ($f'_s = 0\cdot79$), but equation (8) should be used if $D < V < 2D$. . .

(6.2.2) *Semi-infinite Source Correction*

A different method of assessing the head shadow effect is to consider the row of lamps as two semi-infinite sources on either side behind the head. The shadow factor then becomes

$$f''_s = 2ER/J\cos\beta \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

where $ER/J\cos\beta$ can be obtained from Fig. 2 of this paper, taking $X/R = -\frac{1}{2}D/V$.

In our example, for $X/R = -\frac{1}{2}D/V = -0\cdot17$ we obtain $f''_s = 0\cdot79$.

This is a good agreement. The linear approximation of equation (4) would have given a shadow factor of 0·83, which is still quite fair for practical purposes.

(6.3) Experimental check

We are now able to design for the required level in the inspector's own shadow:

$$J = J_u/f_s = 195/0\cdot79 = 250 \text{ lm/ft r}.$$

A twin row of 4 ft 40w lamps with a reflector magnification of $m = 1\cdot9$ would give a sector flux of $J = 1\cdot9\times2\times1600/2\pi4 = 240$ lm/ft r.

Allowing for a certain amount of reflected light

Table 3

Relations between Flux, Intensity and Sector Flux

	Individual Source	Long line source, or row of sources	
Shape of Source	Total Flux F	Flux F_1 per unit length	Ratio J/I_o of Sector Flux to Intensity per unit length
Sphere	$4\pi I$	$2\pi J$	2
Diffusing cylinder	$\pi^2 I_o$	$2\pi J$	$\pi/2$
Fluorescent lamp	$9\cdot25I_o$	$2\pi J$	1·47
Diffusing plane or concave diffuser	πI_o	$2J_o$	$\pi/2$

I_o is intensity (for individual source) or intensity per unit length (for long line source), in direction normal to axis of source.
J_o is sector flux in direction normal to plane of source.

this seemed adequate and a twin row of 'colour matching' lamps was installed.

Measurements after about 200 burning hours gave 49 lm/ft² unobstructed, and 39 lm/ft² in the person's shadow. The measured shadow factor of 0·82 was higher than the calculated one, perhaps due to reflected light, but more likely due to low experimental accuracy.

Allowing for light depreciation, we find that the design aim was achieved with satisfactory accuracy.

The conclusion is interesting, that with linear lighting from behind a standing person leaning slightly forward, the head shadow reduces the illumination by about one fifth. The shadow is 'soft' and hardly noticeable. The shadow factor, however, becomes appreciably lower if an observer's head is closer to the work.

(7) Flux Relations

Some fundamental relations between flux, intensity and sector flux for a few types of ideal light sources and for fluorescent lamps are given in Table 3. Although these relations seem at first sight academic, since real fittings always deviate from ideal types, they can be very helpful in practical design, e.g. estimating for local lighting or predicting polar curves of light distribution.

(8) Conclusion

This paper dealt with some simple methods for calculating illumination which may be useful for practical design. They are applicable in the laboratory too, but more complex methods are often required there for the sake of greater accuracy.

To the designer, the calculation of illumination should only be a beginning: it must be followed by considerations of glare, colour and appearance. In recent years methods of computation, such as Waldram's design of the visual field[16] and various assessment methods for glare have been developed which establish quantitative ways of coping with 'quality' in illumination design, and thus make complex and somewhat vague relationships more tangible. Calculations, whether those discussed here or more advanced ones, can never be a substitute for good taste and practical experience; but quantitative checks can take the 'miss' out of hit and miss methods, and preliminary calculations are usually cheaper than alterations to a completed installation.

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Discussion

MR S. S. BEGGS: I think that few people will disagree with Dr Einhorn, at least on the first paper, to which I propose to restrict my comments. Lighting calculations provide a paradise for mathematicians, and most of us know the works of Higby and Parry Moon; mathematics to such depth are useful, but not to the practical lighting engineer, who is much more concerned with a fairly precise method which will give a practical answer. My only difference of opinion with the author is on just how much mathematics is permissible.

Dr Einhorn points out discrepancies in the Coefficient of Utilisation tables given by different authorities. I was not at all appalled by these, for looking at the figures in his paper the agreement seemed to me surprisingly good, except possibly for very large rooms. I do wonder whether, whatever method of calculation or mathematics we adopt, we can hope to get a 'true' value with tolerances much better than these discrepancies, bearing in mind that in practice one does not know the factors to high precision, especially in the less straightforward problem.

The section on point sources I consider the most valuable part of the paper. The ordinary engineer has been rather frightened off treating lighting sources as point sources; the paper shows that for most practical purposes he can treat almost any fitting as a point source. Table 2 gives valuable data on this question; the last column shows that for any source in the very representative range considered there one can go down to about twice the maximum dimension of the source and still be within 5 per cent of the correct figure, which is as much as can be expected. For the practical man, therefore, the rule

is simply 'you can go down to a distance twice the size of your fitting, and be quite good enough'.

I query whether in practice there is any great value in equation (2a) which gives a more precise formula for fluorescent lamps, or in the suggestion that for industrial dispersive reflectors one should measure the distance from a point part-way between the light source and the edge of the reflector. Dr Einhorn has let his fondness for mathematics get the better of him here, and I doubt whether such refinements are necessary.

The section on line source calculations is quite important, and the practical engineer has got to get acquainted with the idea of sector flux; but this is a more complex idea than those associated with point sources, and I am not sure that the attempted simplification here really does help. The man who uses it would probably do better to go back to the original papers mentioned. However, Dr Einhorn might have gone a step further in simplification, by not attempting to be so precise and adopting one formula for all cases. Sector flux depends on the integral of the polar curve in the plane of the axis of the fitting, but it is surprising how small is the difference in its value for widely differing curves. In his original paper Dr Einhorn shows that if I_0 is the normal intensity per unit length of the fitting or lamp, the sector flux is given by $2I_0$ for a constant intensity distribution, and is $(\pi/2)I_0$ and $(4/3)I_0$ for intensity varying as $\cos\theta$ and $\cos_2\theta$ respectively. The constant intensity case is rare, and most fittings have a curve approximating $\cos\theta$ or $\cos_2\theta$. It would be more useful for the practical man to take one simple formula for the whole lot, and I propose that we should take $1{\cdot}5$ times the intensity I_0 (or more correctly $1{\cdot}5 \times 1/C$ where I is the maximum intensity of the fitting in the axial plane concerned and C the spacing) for all line source calculations; the accuracy of the assessment would not be affected to any great extent.

The other important feature for the finite line source is the fall off or end effect. For the same wide range of polar curves, the illumination at a point at a distance from the end equal to the mounting height differs by closely 10 per cent from the value at a great distance from the end (in either direction); thus Dr Einhorn's linear approximation (Equation 4 and Fig. 2), leading to the simple rule of steady rate of change from nought to $1{\cdot}5\ I_0$ between these two points, would be quite good enough for all practical purposes.

DR J. W. T. WALSH: I should like to make a few very general remarks, rather on the lines of those made by Dr Einhorn at the beginning of his presentation.

Those of us who have had perforce to deal with precise measurements are liable to forget the comparatively large tolerances in the data on which practical calculations have to be based. There is need for an interpretation, or adaptation to the needs of the everyday lighting engineer, of many lighting calculations, not only those described in the paper. Dr Einhorn has done well to draw our attention to the matter, and in fact a good deal more should be possible on the lines he has indicated.

This work might well be continued so that the practical lighting engineer could have a kind of *vade mecum* which would enable him to use approximations that the man with the necessary theoretical knowledge behind him could guarantee to produce a satisfactory result to the sort of accuracy which the engineer required.

I am afraid I cannot follow Mr Begg's trouble with the use of sector flux and in this matter I am entirely on the side of Dr Einhorn.

MR A. G. PENNY: I feel that care should be taken to prevent misleading conclusions being drawn from adopting a precision of 5 per cent in illuminating engineering calculations. It seems to me very doubtful whether the elements which go to make such a calculation can ever be assessed with such accuracy. For instance, when one considers the effect of individual variation, ambient temperature, circuit design and supply voltage, it will readily be appreciated that the light output of a fluorescent tube in service may be very different from the nominal figure in a British Standard. If the practical result agrees with calculations to such an accuracy I submit that this is only evidence that errors very much larger than 5 per cent have been offset by other large errors. It is dangerous to rely upon variations cancelling each other in this way. Whilst it is important that calculations should be as precise as possible, it is equally important that the scale of possible variations should be assessed as precisely as possible, so that an intelligent estimate can be made of the difference which may arise between theory and practice. It is only in this way that the lighting engineer can be sure of avoiding the twin pitfalls of a cheap, inadequate installation on the one hand and of an expensive, extravagant job on the other.

MR J. A. LYNES: In the spoken version of his paper the author implied that the polar curve of sector flux always has the same shape as the polar curve of intensity in the plane normal to the axis of a line source. This cannot be true unless the shape of the axial polar curve of intensity is the same for all planes around the light source. This condition would not generally be fulfilled by louvred fluores-

cent fittings, especially those with reeded side panels, or by rows of point sources with re-entrant polar curves.

MR H. E. BELLCHAMBERS: Referring to the question raised by Mr Lynes regarding the shapes of the polar curves of sector flux and of intensity in the axial planes, I have measured some fluorescent lamp fittings to check possible differences in these polar curves. The fitting which had the greatest differences consisted of a louvre system underneath, diffusing side members, and openings above the side members emitting light directly from the lamps. For this fitting, the J/I_0 factors determined for a number of axial planes varied between 1·2 and 1·4. This is well within the order of accuracy suggested by Mr Beggs, and in practical installation calculations the errors involved are quite small.

THE AUTHOR (in reply): I agree with Mr Penny that the data entering lighting calculations are often uncertain and variable. They affect the accuracy of the result; this must not, however, be confused with the accuracy of the calculation method itself. Dr Walsh evidently agrees that the uncertainties of data mentioned justify approximations and the use of simple concepts for complex reality, such as that of intensity for sources which are not points, or that of sector flux for line sources which are not infinite. It was the very theme of this paper to recommend boldness in calculating, but at the same time to establish the limits of simple methods. I agree with Mr Beggs that the linear approximation for the end effect, and a J/I_0-factor of 1·5 are good enough for most fluorescent fitting lay-outs except louvred ones. Mr Beggs' view that the idea of sector flux is complex may perhaps apply to some of the underlying theoretical considerations, but the use of the sector flux concept in practice is very simple indeed. Mr Lynes is quite correct in stating that polar curves of sector flux and intensity are not inherently identical. Mr Bellchambers gave the answer; in practice they differ very little as a rule.

I do not share Mr Beggs' satisfaction with the agreement of utilisation factor figures. The discrepancies are in many cases well over 10 per cent—sometimes even as high as 40 per cent—for the same data. Mr Beggs queried the utility of equation (2a). It is perhaps more useful to the photometrist than to the designer.

UDC 612.843.367 :628.93

Pre-determination of Direct Discomfort Glare

By H. D. EINHORN, Dr.-Ing., Ph.D., A.M.I.E.E, M.(S.A.)I.E.E. (*Fellow*)

Summary

A formulation for the practical pre-determination of direct discomfort glare is proposed on the Harrison-Meaker pattern, but based on later laboratory research. A summation theorem is postulated, which states that a glare rating must be proportional to source area if simple additivity is desired. A location coefficient chart has been derived from Luckiesh-Guth's position indices, and $a\lambda$-charts are given which allow for orientation as well as position of glare sources. An analytical expression for the location coefficient dispenses entirely with charts.

(1) Introduction

Much attention has been given in recent years to quantitative methods of glare analysis, and justifiably so. To develop a check method acceptable to the practical designer three steps are necessary: laboratory research and field observations, agreement on the factors that matter and development of a rapid and convenient assessment method.

A distinction can be made between discomfort and disability glare, as well as between direct and reflected glare. While reflected glare is important and should not be underrated, it has hardly been scientifically explored and, for the time being, will have to be attacked by geometrical reasoning coupled with commonsense rather than by calculation.

Laboratory research on direct discomfort glare[1–11], in spite of divergences between the results obtained by different methods and uncertainty on some of the factors influencing it, has yielded enough information to justify discomfort glare formulation. Some or all of the following factors may have to be taken into account:

(i) luminance of glare source;
(ii) luminances of the rest of the visual field, preferably with a distinction between the luminance in the immediate visual vicinity of the glare source and the general luminance pattern determining adaptation;
(iii) size of glare source, fundamentally in terms of visual solid angle, often more conveniently expressed as area seen;
(iv) position of glare source, especially its angular displacement from the line of sight;
(v) shape of source.

(2) Previous Proposals

The major problem in forging the complex results of laboratory research into a useful practical tool is simplification, and it is indeed a formidable task.

After some concentration on luminances only and a demand in America for limited brightness-ratios, which would have rated a Sumpner-sphere as an ideal interior while condemning many good and interesting installations, Harrison and Meaker in the USA[1] proposed a glare factor which was a function of size and position as well as of luminances. Their formulation is probably the most convenient proposed so far, but the data on which the published location coefficient chart was based are now obsolete.

Proposals by Hopkinson and Petherbridge[4] and by Luckiesh and Guth[3] are based on their own thorough laboratory researches, but are presented in a form which, even with the aid of charts or monograms[3,15], is not very convenient for practical design. In particular the use of the solid angle (ω) is cumbersome.

The influence of the shape of a glare source is complex and hardly important enough for inclusion in a practical formula.

The British proposal to the CIE in 1955[12] probably contains the essential factors*:

$$G = B_s^{n}\omega^{m}B_b^{-p}f(\theta)f(B_i) \quad \ldots\ldots (1)$$

The additional suggestion of making $m=1$, $p=1$, $n=2$, adopts the relative weight allotted by Harrison and by Hopkinson to luminance and size of source and simplifies the formula:

$$G = B_s^{2}\omega B_b^{-1}f(\theta)f(B_i) \quad \ldots\ldots (2)$$

Hopkinson's recent proposal[21], $GC = B_s^{1.6}\omega^{0.8}B_b^{-1}$, would lead to summation difficulties.

(3) Summation of Glare Factors

Glare from a number of sources is cumulative and the usual practice is to add up glare factors of individual sources in the field of vision.

The simplest assumption (see Appendix 2 for others) is that adding glare sources is equivalent to

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* For definitions of symbols used in all formulae, see table of symbols at end of this paper.

enlarging a single glare source—in other words that two sources each of area A_s are as glaring as one source of area $2A_s$. This requires a glare factor in which the *exponent of the area or solid angle is unity*. This is quite compatible with experimental results which have established the *relative* importance of luminance, area and position, i.e. equation (1) can be normalized to make $m=1$.

To demonstrate that anomalous results are otherwise obtained, let us apply the formula[21] $GC=B_s^{1.6}\omega^{0.8}B_b^{-1}$ first to a single 8 ft fluorescent lamp, and then to two 4 ft lamps of the same luminance, mounted end-to-end. The glare constant computed for the two separate lamps would be 15 per cent higher than that for the single larger lamp, although they look the same and would give the same amount of glare. One could in this way double the glare constant by splitting a large source into thirty small parts.

On similar grounds, G. A. Fry[15] has criticized a square root summation method of combining glare factors proposed by S. K. Guth[13]. Proposals based on luminance addition[6,11] also lead to anomalies of this kind. And, of course, logarithmic glare indices[19] are not additive; the summation over a number of glare sources must take place *prior* to taking the logarithm: $GI=\log\Sigma(B_s^2\omega B_b^{-p})$.

No claim is made regarding the biological interpretation of additivity. Only a mathematical condition has been stated for adding up glare ratings consistently.

(4) Direct Discomfort Glare Formula

The glare formula proposed below (equation (3)) is very similar to that of Harrison and Meaker[1], but is based on more recent research data. The use of area (A_s), multiplied by a location coefficient (λ) which allows for distance as well as direction, is more convenient for practical design work than the determination of solid angles (ω) and allowance for displacement angles (θ).

$$DGF=\frac{A_sB_s^2\lambda}{H_s^2B_b\sqrt[3]{B_i}} \quad \ldots\ldots\ldots\ldots (3)$$

Here A_s is in sq ft, B_s in units of 1,000 ft-L, B_b and B_i in units of 10 ft-L. H_s is the height in ft above eye level, which is usually taken as 4 ft for sitting and 5½ ft for standing persons. The $1/\sqrt[3]{B_i}$ factor may be considered valid, so long as $0{\cdot}01<B_i<\sqrt{B_sB_b}$ which is usually the case.

The location coefficient λ can either be taken from the contour chart of Fig. 1, or it can be calculated as

$$\lambda=\frac{55}{2+d^2/10+5/d^2+2s^3/d} \quad \ldots\ldots\ldots\ldots (4)$$

This expression, which is well adapted to slide rule work, has been derived empirically to fit the curves of Fig. 1; the agreement should be adequate for practical purposes.

By substituting (4) into (3) a purely analytical glare formula is obtained, not dependent on graphs or tables, which could easily be included in handbooks, codes or specifications.

The development of equations (3) and (4), with reasons for the choice of exponents, is given in Appendix 1.

(5) Area Reduction Rules

The projected area (or 'area seen') of a source which enters the glare formula is dependent on its position and orientation. It is often convenient to use a foreshortening factor or 'area factor' $\alpha=A_s/A$, where A is the 'normal' area visible, e.g. length × diameter in the case of a fluorescent lamp or the actual surface area in the case of a plane diffuser. A summary of area factors for some typical lay-outs in terms of relative distances d and s may be useful.

For transverse diffusing cylinders, i.e. cylindrical diffusing fittings across the line of vision:

$$\alpha_{td}=\sqrt{(1+d^2)/(1+d^2+s^2)} \quad \ldots\ldots\ldots\ldots (5)$$

For longitudinal diffusing cylinders, i.e. cylindrical fittings parallel to the line of vision:

$$\alpha_{ld}=\sqrt{(1+s^2)/(1+d^2+s^2)} \quad \ldots\ldots\ldots\ldots (6)$$

For plane horizontal diffusing sources, such as recessed fittings with flush diffusing panels, or concave diffusing sources with plane horizontal openings such as coffers:

$$\alpha_p=1/\sqrt{1+d^2+s^2} \quad \ldots\ldots\ldots\ldots (7)$$

For fluorescent lamps the reduction of luminance at acute angles can be combined with the foreshortening effect. The following are relatively simple and quite good approximations:

For transverse fluorescent lamps:

$$\alpha_{tf}=(1+d^2)/(1+d^2+s^2) \quad \ldots\ldots\ldots\ldots (8)$$

For longitudinal fluorescent lamps:

$$\alpha_{lf}=(1+s^2)/(1+d^2+s^2) \quad \ldots\ldots\ldots\ldots (9)$$

As an alternative to these equations, contour charts similar to the location coefficient chart can be used. (See for example Fig. 6 in reference (1).) More useful are charts or tables giving the product $\alpha\lambda$ of area factor and location coefficient, as shown for example in Figs. 2 to 4. Since the other factors are usually the same for all glare sources in an installation, summation need only be carried out over this $\alpha\lambda$-product;

$$DGF=\Sigma\frac{A\alpha B_s^2\lambda}{H_s^2B_b\sqrt[3]{B_i}}=\frac{AB_s^2}{H_s^2B_b\sqrt[3]{B_i}}\Sigma\alpha\lambda \quad \ldots. (10)$$

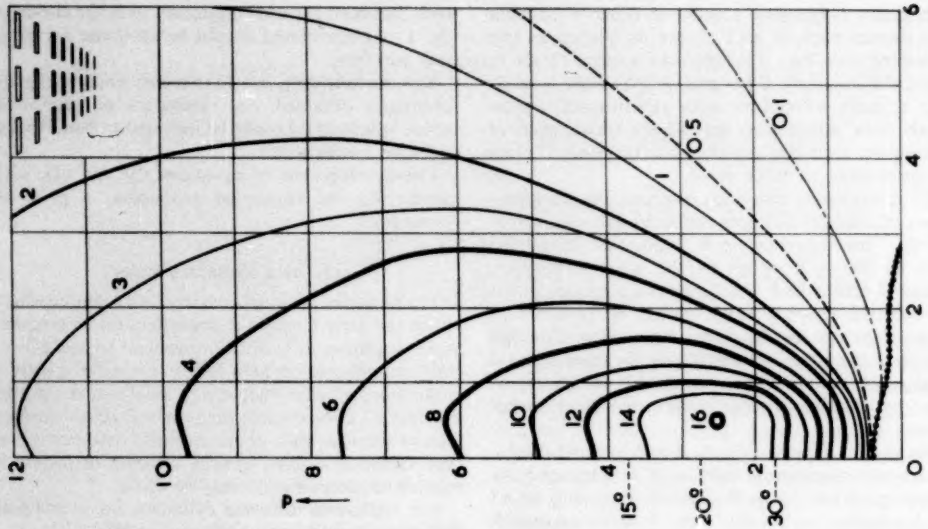
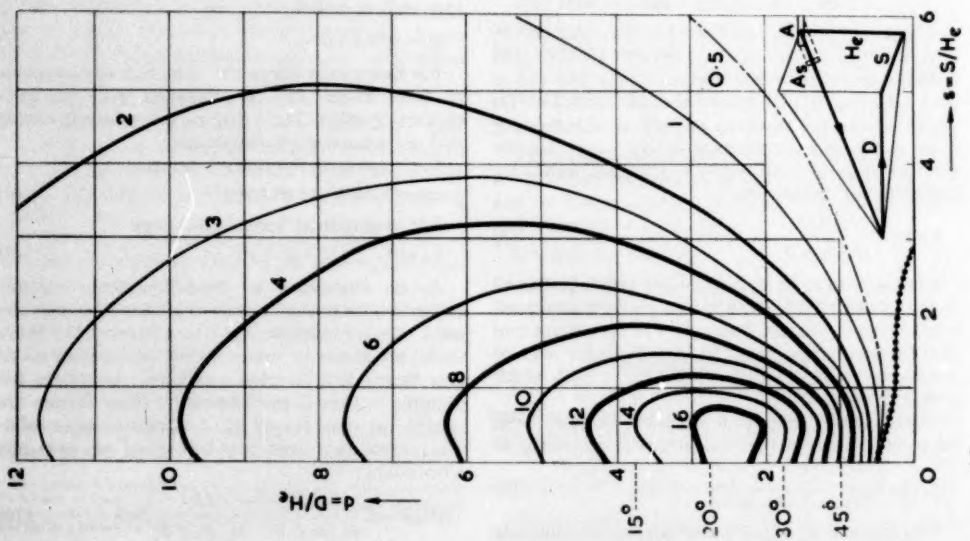


Fig. 1. (left) λ-chart. Location coefficient, calculated from Luckiesh-Guth position index as $\lambda = 600\ p^{-3}\ (1 + d^2 + s^2)^{-1}$. *Inset shows dimensions;* $d = D/H_e$, $s = S/H_e$. *Pearl-line near origin shows boundary of visual field.*

Fig. 2. (right) λa_{45}*-chart. Location coefficient x area factor for transverse fluorescent lamps. Note cut-off angles. Inset symbolises lay-out.*



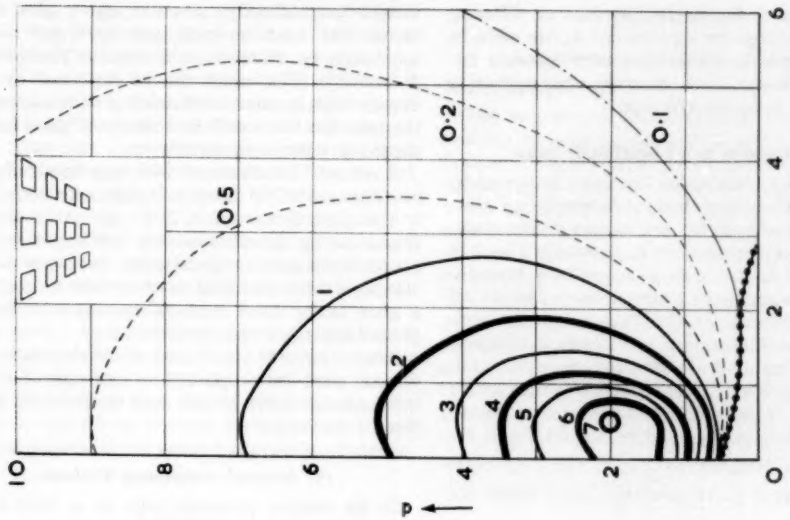


Fig. 4. λa_p-chart. Location coefficient x area factor for plane horizontal diffusing panels, or concave diffusers with co-planar horizontal edges.

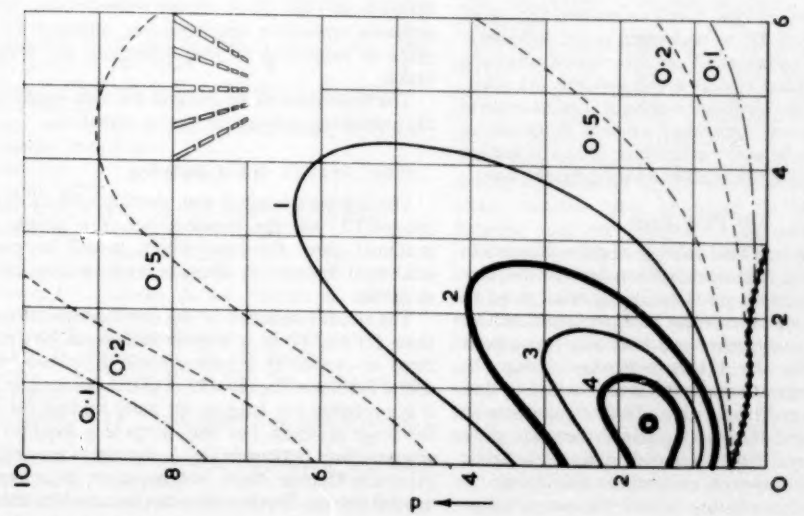


Fig. 3. λa_y-chart. Location coefficient x area factor for longitudinal fluorescent lamps.

With transverse fluorescent lay-outs or diffusing incandescent fittings the variation of A_s can often be ignored and simple summation over location coefficients is sufficient, since the error when neglecting foreshortening is on the safe side.

(6) Conversion to a Logarithmic Scale

A logarithmic glare index has been proposed by Hopkinson[21]. Precedents from well-established practice can be found both for and against it; for example, the scale of illumination in lumens per sq ft is linear, but the decibel scale in acoustics is logarithmic. The extra computing labour has to be set off against the advantage of obtaining a number correlating better with sensation and practical effectiveness. There is certainly no difficulty, provided addition over all glare sources has been performed before converting to a logarithmic scale, e.g. a Direct Discomfort Glare Index could be defined simply as:

$$DGI = 10 \log 100\Sigma(DGF) \quad \ldots\ldots\ldots\ldots\ldots \quad (11)$$

For conversion to Hopkinson's glare index, see Appendix 3.

(7) Cut-off Angles

A comparison of Fig. 2 and Fig. 3 confirms the well-known fact that a longitudinal lay-out of fluorescent fittings is much less glaring than a transverse lay-out. Transverse bare fluorescent lamps should be avoided, except in small rooms, and the chief aim of industrial reflectors is the elimination of glare from all lamps below a visual angle corresponding to the cut-off angle of the luminaires (measured from the horizontal).

An inspection of Figs. 1 or 2 shows that the use of a cut-off angle of 30°, in preference to the commonly found cut-off angles of 15° or 20°, would eliminate an important glare region which includes the maximum value of the location coefficient. Unless vertical illumination is very important, a cut-off in the region of 30° seems to be well worth while, even if it implies the need of a slightly smaller spacing/height ratio.

(8) Field Tests

Checking the practical validity of glare assessment methods by field tests is important, but the low precision of allocating a quantitative appraisal value to a completed installation must be appreciated. Whilst appraisal tests in America[1] and Australia[17] gave good agreement with the Harrison-Meaker rating, E. Rowlands [18] found some discrepancies which at first sight are rather disconcerting. Two installations in particular, *E* and *H*, upset agreement between glare factor rating and field appraisal; a closer analysis of these might, however, restore our confidence.

Installation *E*, consisting of bare fluorescent lamps viewed longitudinally, gave too high a glare factor value. The same anomaly can be found in field appraisals by Harrison and Meaker (installations *N* and *K*)[1]. This result can be explained by their unduly high location coefficients at wide angles, and the new location coefficient charts (Figs. 1 and 3) should give better agreement.

Rowlands' installation *H* with deep bowl reflectors containing MBF/U lamps was assigned a surprisingly low glare factor value. This may prove that information on the effect of very low immediate surround luminance is inadequate, but there is also reason to think that with more realistic assumptions a glare factor value more in keeping with the appraisal test might have been found.

After a possible adjustment of the two cases mentioned, glare factor prediction and appraisal tests will probably differ by less than the standard deviation of the latter.

(9) Integral Assessment Methods

In the method proposed here, as in most of the other methods, the glare ratings of individual sources are calculated and added up. This is the only possible way of dealing with irregular lay-outs, and seems worth the trouble for important installations or for rooms with only a small number of glare sources.

For routine jobs of regular lay-out, 'integral' methods are desirable, which would give the rating for a whole room without preliminary computation for individual sources. Tables based on precalculation, like those published by Meaker,[1] fall under this heading. So does the Australian specification[20] of luminances for given room dimensions, which achieves admirable simplification, although at the price of neglecting varying tolerances for different tasks.

The derivation of an integral formula might form an interesting subject for future research.

(10) Conclusion

The author's original aim, starting with an earlier proposal[23], was the development of a simple and practical glare formula, which would be purely analytical in order to dispense with auxiliary charts or tables.

The result contained in the combination of equations (3) and (4) is so simple that it can be memorized or carried in a pocket-book. It should prove useful as long as the number of glare sources is small; it is probably too lengthy for daily routine use and for large lay-outs. For this purpose a location coefficient chart is given in Fig. 1, similar to the original Harrison-Meaker chart, but based on later experimental results. Further time can be saved by the use

of $\alpha\lambda$-charts (Figs. 2 to 4), which allow for both position and foreshortening of sources; they can be applied to regular as well as irregular lay-outs.

No claim is made that the formulation proposed is necessarily the best. A formula based on AB_s^3 instead of AB_s^2 might agree with experimental facts over a wider range (see Appendix 1). The relative weight given to background luminances could be improved when more experimental evidence becomes available. Any new formula must, however, retain proportionality with source size if summation of individual glare ratings forms part of the method. Conversion to a logarithmic glare index is quite easy, but logarithmic indices are not additive.

The author agrees with proposals that different tasks require different glare rating limits. It was not the aim of the paper to lay down what these ratings should be or how they should be presented, but merely to contribute towards finding a simple and practical method of obtaining a glare rating quantity.

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Appendix 1

Derivation of the Glare Formula

Source luminance B_s

The necessity of proportionality for area, i.e. of making $m=1$ in equation (1), has been discussed in Section 3. Experimental results on the relative weight of luminance and area are conflicting, the exponent n for the source luminance varying between two[2,4] and more than three[3,6,10]. In Fig. 5 is shown the B_s and ω relationships for a constant glare rating, derived from various published data. A likely figure of $1{\cdot}6/0{\cdot}6=2{\cdot}7$, has been mentioned[9], but a fractional exponent would complicate slide-rule work considerably. A bold decision on either $n=2$ or $n=3$ seems to promise a more practical compromise between simplicity and accuracy. Although a greater number of research results seem to support a choice of $n=3$, the fact that recent British proposals[21,22] retain the previously proposed $n=2$ has been decisive in adopting it here.

Background luminance B_b and B_i

A formulation convenient for slide rule operations is also desirable for B_b and B_i, the general and immediate background luminances. In most of the laboratory investigations a luminance value was obtained which covered both adaptation and contrast grading, since usually $B_b \propto B_i$. Published information on the difference between the two effects is meagre and an accurate assessment of $f(B_i)$ is likely to be complex.

The tentative proposal of $f(B_i)=B_i^{-1/2}$, coupled with the British proposal of B_b^{-1}, achieves the following:

For $B_i=B_b$ we obtain $B_b^{-1.33}$ which is between the relative weights given to B_b and ω by different authors: $\omega B_b^{-1.25}$ would correspond to Hopkinson's $\omega^{0.8}B_b^{-1}$; Luckiesh-Guth's weighting varies between $\omega B_b^{-0.9}$ and $\omega B_b^{-1.4}$, that of Arndt, as well as of Vermeulen-de Boer is in the order of ωB_b^{-2}. For $B_i \neq B_b$ the relative weight given to each is somewhere between that proposed by Harrison and Meaker and the results of Petherbridge's and Hopkinson's investigation[4] on the effect of B_i. *Perhaps still greater weight should be given to B_i and less to B_b, since a fractional exponent for B_b relative to ω would be consistent with increased glare resulting from an increase in the number of diffusing fittings in a room in spite of raised adaptation level, as is sometimes observed in practice.* Nevertheless conclusive experimental information is insufficient to warrant an alteration of the CIE proposal of B_b^{-1}.

It has been shown[4] that B_i has an optimum value and that a further increase beyond this will turn the surround into a glare source. For this reason the

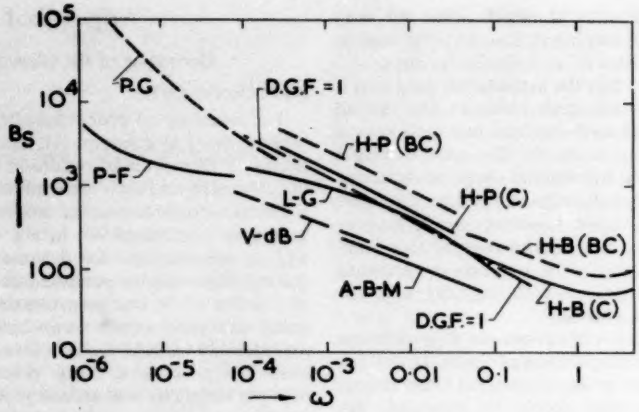

Fig. 5. Comparison of experimental results

Source luminances against size of source, all for $B_b = B_i = 10$ ft-L. and for equal criterion.

H-P (C): Criterion C (just acceptable), reference (4).

H-P (BC): midway between B and C, reference (4).

H-B (C): Criterion C, reference (9). *H-B (BC): midway between B and C, reference* (9).

L-G: criterion BCD, reference (3).

V-dB: reference (6). *P-F: reference* (7). *P-G: reference* (8). *A-B-M: reference* (10).

DGF=1: From equation 3.

(*See also reference* (19).)

Note: The slope of any individual curve (which represents the index of ω relative to that of B_s) is more significant than its level.

validity of having $\sqrt[4]{B_i}$ only in the denominator must be limited; giving $\sqrt{B_s B_b}$ as the upper limit for B_i is somewhat arbitrary, but conservative[4].

Location Coefficient λ

The location coefficient λ shown in Fig. 1 has been derived from the Luckiesh-Guth[3] position indices P by the relation

$$\lambda = \frac{600}{(1+d^3+s^3)P^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (13)$$

Fig. 1 shows a maximum at $D/H = 2{\cdot}5$ similar to the well-known graph of Harrison and Meaker.[1] The two graphs, however, differ noticeably at wide angles when $s > d$.

The numerator 600 was chosen to normalize the discomfort glare equation (3) so as to make unity DGF slightly more stringent than Hopkinson's 'just acceptable' criterion and rather more tolerant than Guth's BCD criterion. The corresponding line in Fig. 5, $\omega(B_s/P)^3 = 1660$, *just* intersects the 10 ft-L BCD curve.

That equation (13) contains P^{-3} is a corollary to our assumption that the glare effect is constant along a line $B_s^3\omega = $ constant. Any such line can agree with the BCD criterion in not more than two points, and discrepancies of a factor of two or even more can occur for small bright sources. Discrepancies of this order, however, are unavoidable and permissible in a field where experimental data differ considerably. In Fig. 5 the curvature of the Luckiesh-Guth BCD lines is just the opposite to that over a wider range containing Hopkinson's and Bradley's results for large sources and Putnam's results for small sources.

Analytical expression for λ

In the analytical expression for the location coefficient (equation 4), the $d^3/10$ term allows for the decrease of ω with inverse square distances; the $5/d^3$ term allows for the decrease of λ due to vertical angular displacement, and the $2s^3/d$ term for the effect of sideways displacement. Coefficients were found empirically and, although simplicity was aimed at rather than accuracy, it is hoped that equation (4) agrees with experimental facts well enough for practical purposes, at any rate better than a previous proposal[22], $\lambda = 29/(1+d^2/40+s^2/2)$ for $d > 0{\cdot}6$, which was rather too rough an approximation.

Appendix 2

Super-Additivity

Recent research[11, 15] has indicated that a number of discrete glare sources may be more glaring than a continuous source of the same total size ('super-additivity. This is plausible, if one assumes that stimulations in neighbouring sections of the retina inhibit each other and thereby mitigate the glare sensation, resulting in a proximity effect most pronounced in a compact continuous source. Super-additivity could thereby be explained, but one would also expect a more pronounced effect of source shape than is usually found.

For practical calculations one could adopt different additivity rules for contiguous sources and for discrete sources. This in fact has been done by authors[11, 13, 16] who propose adding glare factors which are not proportional to the size of the source ($m \neq 1$). These proposals have the merit of simplicity, but it may be difficult to apply them to linear lighting lay-outs or to other arrangements of glare sources which fall into the transition region between a compact continuous source and clearly separated point sources. Further experimental evidence on their validity for different source arrangements seems desirable.

Meanwhile it seems straightforward and expedient to assume the same additivity law for contiguous and discrete sources of any shape, and therefore to adopt a glare factor expression proportional to source size, as has been done in this paper. The glare factors obtained by the charts and equations presented here could, however, be summated by a non-linear method, writing

$$DGF_T = (\Sigma DGF^m)^{1/m}$$

in which, for example, for Hopkinson's rule $m = 0{\cdot}8$, for Guth's $m = 0{\cdot}5$, for Arndt's $m = 0{\cdot}33$.

Appendix 3

Comparison of Glare Ratings

Different glare ratings are as a rule equivalent for a limited set of conditions only, and generalized statements can be misleading.

The following relations can be established, however.

DGF and BRS Glare Constant

If the BRS glare constant [21] is

$$GC = (B_s/P)^{1.6}\omega^{0.8}/B_b,$$

then one can show that for a single glare source and if $B_i = B_b$:

$$GC = 38\ DGF^{0.8}(B_i/10)^{0.067} \quad \ldots\ldots\ldots\ldots \quad (14)$$

This equivalence holds good for any luminance and size of source and for any position, if P is the Luckiesh-Guth position index.

Some equivalent ratings are given in Table I.

DGI and Hopkinson's GI

If Hopkinson's glare index[21] is

$$GI = 10 \log GC,$$

from equation (14) it follows that for a single glare source and if $B_i = B_b$

$$GI = 8 \log (100\ DGF) - 0{\cdot}9 + 0{\cdot}67 \log B_i \quad \ldots \quad (15)$$

or

$$GI = 0{\cdot}8\ DGI - 0{\cdot}9 + 0{\cdot}67 \log B_i \quad \ldots\ldots\ldots \quad (16)$$

where DGI is defined by equation (11).

See Table 1 for some equivalent ratings.

Table I

Some Glare Ratings Compared

DGF	0·2	0·5	1·0	2	5
DGI	13	17	20	23	27
BRS GC	10	22	38	66	140
Hopk. GI	10	13	16	18	21
H-M GF*	8	20	40	80	200

Assumption: $B_b = B_i = 10$ ft L.
* $d = 3$; $s = 2$

DGF and Harrison-Meaker Glare Factor

The Harrison-Meaker glare factor is

$$GF = A_s B_s^2 LF / H_e^2 F,$$

where the location coefficient LF is taken from Fig. 2 in reference (1) and A_s is in square inches, B_s is in kilo ft Lamberts, and F is the surround factor. One can show that $GF = 144\ (LF/\lambda)\ DGF$, for $B_b = B_i =$ 10 ft L, so that $F = 1$. This equivalence holds for any luminance and size of source. In the position of maximum glare effect ($d = 2{\cdot}5$, $s = 0$)

$$GF = 35\ DGF \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (17)$$

A comparison of the location coefficient charts shows that for other positions the GF/DGF ratio may vary between say 3 and 200 with typical values between 40 and 50.

DGF and Luckiesh-Guth's BCD

One can show that for $B_b = B_i = 10$ ft L,
DGF = 1 corresponds to the BCD criterion[3],
if $\omega = 0{\cdot}012$, $B_s/P = 370$ ft L, and also
if $\omega = 0{\cdot}046$, $B_s/P = 190$ ft L.

This applies for all positions, but not for other

angular sizes of source. For example, DGF=0·35 for the BCD values $\omega = \cdot 0006$, $B_s/P = 1{,}000$ ft L.

The maximum value of DGF is 1·08, for the BCD values $\omega = 0 \cdot 02$, $B_s/P = 300$ ft L (still assuming $B_b = B_i = 10$ ft L).

No simple power law can be equivalent to the BCD, as defined by Luckiesh and Guth, in more than two points. The statement[15] that 'BCD corresponds to a Harrison-Meaker glare factor of 55·6' is valid only under one specific set of conditions.

List of Symbols

'Source' means glare source.

A_s = 'area seen' of the source, i.e. area projected normal to a line from source to eye.
B_s = luminance of the source.
B_b = general background luminance, which determines adaptation.
B_i = luminance of immediate visual surround of source, which determines contrast grading.
H_e = height of source above eye level.
D = horizontal distance of source in direction of regard.
S = horizontal sideways displacement of source.
$d = D/H_e$ = distance of source in terms of H_e.
$s = S/H_e$ = sideways displacement of source in terms of H_e.
θ = angular separation of source from line of sight.
m, n, p, are indices in general equation for glare rating (equation (1)).
$\alpha = A_s/A$ = area factor to allow for foreshortening of source.
λ = location coefficient.
ω = solid angular size of source (in steradians).
P = 'Position Index' as defined by Luckiesh-Guth[3].
G = 'Glare constant' as defined by British National Committee[12].
DGF = Direct discomfort glare factor, as defined in this paper.
DGI = Direct discomfort glare index, as defined in this paper.
GF = Glare factor, as defined by Harrison-Meaker[1].
GC = BRS glare-constant[21].
GI = Glare-index, as defined by Hopkinson[21].
VCI = Visual comfort index.
BCD = Border line between comfort and discomfort (Luckiesh-Guth[3]).

Discussion

DR R. G. HOPKINSON: Glare is very much a topic of interest at the moment so we are able to give full credit to Dr Einhorn for the admirable work which he has done. He re-states concisely many of the basic conclusions of the researches so far completed, and offers his own system by which they can be applied in the service of lighting engineering.

When preparing the paper Dr Einhorn was probably unaware of the full progress of the work of the Luminance Study Group of the I.E.S. Technical Committee, which has led to a method for the determination of glare by the use of tables which avoid the use of a formula. His paper has therefore come too late for it to influence immediate practice in this country, but many of us will examine it with great care because it offers an alternative technique which may possibly prove of advantage, particularly in the incorporation of the Position Index.

Those who work on any aspect of vision research realise that we are dealing with an exceedingly complex human function. The experimental data can be expressed in a variety of ways—graphically, tabular, or by using mathematical symbols—and yet still fail to describe completely what we have discovered in our researches. Consequently approaches to the problem made by those, like Dr Einhorn, with a special gift for arithmetical manipulation, stand or fall by the criterion as to whether or not they simplify the problem of designing better lighting. None of us has had experience of Dr Einhorn's method so we cannot apply this test. It may be relevant to point out, however, that if Dr Einhorn applies the thesis on additivity as described in his paper and splits his source into as many as thirty components, the difference between the glare predicted by this computations and the true glare will be not more than one half a criterion step, a difference hardly sufficient to attract the notice of the majority of ordinary people. The difference between the simple addition of glare constants and the addition according to equivalent area, which was put forward in our paper in 1950, amounts in actual practice to a discrepancy which could only be detected for certain by skilled observers making a direct side-by-side comparison. In fairness to workers in this country I think it should be pointed out that we have always been aware of the errors involved in our compromises and particularly in the adding of glare constants, and have pointed them out ourselves in our original papers and subsequent publications. Moreover, we have also pointed out when these errors matter and when they do not, and this is the important thing. One thing that we have found that does matter is the exponent of the source luminance, relative to that of the surround luminance. The simple square law used by Dr Einhorn, which I originally put forward in 1952, has been subsequently shown not to be sufficiently accurate for design work, and so we have returned to the original formula. (Incidentally this

formula with the 1·6 index was also put forward in 1950, not 1960 as stated in the paper.)

My own hope is that with more frequent use of electronic computers, which should be able to handle the most complex relationships, it will no longer be necessary to simplify the experimental results of visual research in order to make them useful to the engineer. There is, however, still much work for the arithmetician to do in preparing the expressions which the computer will have to use. Dr Einhorn has offered a simplified expression for the effect of the immediate surround to the source which, as he says, is nothing more than a compromise. We have a mass of experimental data at the Building Research Station on this problem and on the effect of the non-uniformity of the source itself. These data have remained in our files for lack of time to codify them. There is certainly a job here waiting for an ingenious mathematician to tackle.

If my remarks sound critical I hope it will be taken by Dr Einhorn as a measure of the interest and stimulus which his work gives me. A fresh and provocative mind working on a problem can do nothing but good by contributing new and valuable ideas and by stirring up the complacency of any of us who have had the field to ourselves for too long.

MR W. BURT: For the past two years the Luminance Study Group of this Society has been studying the subject of glare. Dr Einhorn's paper has, I am afraid, appeared a little too late for consideration by the Group; had Dr Einhorn been in this country two years ago, I am sure he would have had a stimulating effect on their deliberations. The Group studied many installations in an attempt to produce a Glare Code, and it became apparent that glare was not strictly additive using the BRS formula. Perhaps Dr Einhorn's formula has produced the answer. However, many checks have been made using the BRS formula, and the Luminance Study Group were satisfied with the results obtained. Could Dr Einhorn tell us how his formula has stood up to practical tests?

Dr Einhorn says that his formula, although very similar to that of Harrison and Meaker, is based on more recent research data. Am I right in assuming that the DGF method has been produced by reasoning rather than by experimentation and measurements?

I whole-heartedly agree with Dr Einhorn that calculation of the solid angle term is a rather cumbersome process; however, there can be no doubt about the accuracy of the result since it is pure geometry. I have also found difficulty in calculating the luminances of the room surfaces in order to predetermine the 'B_b' term—and I doubt the accuracy of the answer when I get it. Does Dr Einhorn share these doubts?

It is noteworthy that Dr Einhorn agrees with the suggestions of the Luminance Study Group with regard to the idea that different environments may be able to accept different degrees of glare. Although Dr Einhorn says that his paper should not lay down these limits, I wish that he had produced some criteria whereby the answers given by his formula could be related to some visual sensation, and the number given some meaning. Would Dr Einhorn care to suggest some criteria?

MR W. ROBINSON: I hesitate to enter this fray, but I think that we ought to try to get a little bit of perspective into all this. For the last two years we have been trying to put glare calculation into the hands of the ordinary lighting engineer and we believe we have achieved this by the production of Glare Index tables.

In processing the glare formula we had to make a number of assumptions and simplifications, such as that a diffusing fitting could be considered to have a constant luminance. We had to abandon any thought of allowing for immediate background brightness in our data as this would clearly have made the whole thing impossible.

It will be noticed that in each of the alternative formulae mentioned by the Author there is one exponent of unity. If this is applied to the ω term it means that we can sum areas to get the correct result; if the adaptation brightness (B_b) has exponent unity, it means, in fact, that the number of fittings in the installaton does not effect the result. It is not all that important which of the two assumptions we make, since the glare recommendations themselves have been derived by computation from the formula employed and we have thus a mutually consistent scheme; this does not depend on the *absolute* accuracy of the formula, but can be effectively employed provided that the formula adequately indicates the order of glare. Our data have been checked by much field work involving visits to something like 100 installations, and it is on the results of this work that we are basing our confidence in the system.

THE AUTHOR (in reply): The work carried out during the past two years by the I.E.S. Technical Committee and mentioned by Dr Hopkinson, Mr Robinson and Mr Burt is admirable indeed. It has led to the formulation of an 'integral method' which allows a quick and easy assessment of common regular lighting lay-outs. In spite of some doubts about its fundamental basis, there is reason to hope that it will yield useful results in practice. For

irregular lay-outs an 'individual method' is required, i.e. the calculation of glare factors for individual sources and their summation. Here the method proposed in this paper is applicable.

In judging the suitability of any method, I agree with Dr Hopkinson and Mr Robinson that simplification is important. A method is desirable which allows a simple addition of glare factors and leads to consistent results; it was shown in the paper that consistency and simplicity demand unity exponent for area (ω or A_s). Dr Hopkinson claims that the discrepancies due to an area exponent of 0·8 would not attract the notice of the majority of ordinary observers; they are nevertheless disturbing to the designer, who would obtain different glare ratings for the same basic data merely considering one large source as the combination of a number of small ones.

I agree with Dr Hopkinson that the exponent of the source luminance relative to the surround luminance is important. The ratio proposed in the paper is substantially the same as in the BRS-formula if the immediate background luminance (B_i) is combined with B_b. In most of Dr Hopkinson's experiments $B_i = B_b$ (or at any rate $B_i \propto B_b$). Hence B_b becomes $B_b^{1.33}$, and $B_s^2/B_b^{1.33}$ corresponds to a *relative* exponent of B_s of 1·5 which is very near to 1·6.

Unity exponent for the surround luminance B_b is not fundamental, although convenient for devising an integral method (see Mr Robinson's reference to the number of fittings). More important is the ratio between the values of the exponents for area and surround luminance.

It should be realised that the addition of glare constants which contain an exponent of 0·8 for area implies super-additivity. Published information is insufficient to judge whether this is a fair approximation for reality. It is interesting that Table 4 in the 1961 Code (page 34) implies distinction between contiguous and discrete sources, since a proportional increase of flux and of area (hence also of B_b) would yield a lower glare index, whilst an increase in the number of fittings would not alter the glare index (as Mr Robinson correctly pointed out).

In reply to Mr Burt, it is possible that parts of Table 4 in the I.E.S. Code might not have been necessary if the calculation had been based on the formula in this paper. The method proposed in the paper is based on reasoning as well as on experimental facts (see references 1–10). The method has not been subjected to new tests, but there is reason to think that it would avoid certain anomalies found in field tests when using older methods (references 1, 18). The conversion of solid angles to projected area is pure geometry and no inaccuracies are introduced by using A_s instead of ω.

I agree with Mr Burt that the estimate of luminance B_b and B_i is difficult and needs judgment based on experience. Sometimes it is best to use the average luminance of the working area as adaption luminance, i.e. $B_b = \rho_{wa} E_{av}$, because the average illumination is always known and the average reflectance of the working area can be estimated fairly easily.

The I.E.S. criteria can be applied to the method described, as shown in App. 3. To obtain a comparable glare index for a number (n) of discrete glare sources, one could add (2 log n) to the value obtained from equation (15) or (16), e.g. one would add 1·2 for four fittings. The same amount of super-additivity is thereby assumed as is inherently contained in the I.E.S. method based on the B.R.S. formula.

Additions to the List of Members

Fellowship

The Council has accepted the following applications for Fellowship of the Society:

Granville Berry
H. D. Einhorn

Diploma Membership

The Council has accepted applications for the Society's Diploma in Lighting Engineering from the following, who are now Diploma Members:

J. H. Howard
F. M. Pigott
A. Wilson

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Wilson, P. S.	72 Pembury Avenue, Worcester Park, Surrey.

The I.E.S. Code

During the last twenty-five years the Codes published by the Society have done much to secure improved lighting standards. This new edition of the I.E.S. Code takes account of major advances in technical knowledge, modern trends in building practice and the rising standards of industrial efficiency, welfare and safety expected today. It has been prepared to give guidance to engineers, architects, consultants and all concerned with the specification of lighting standards for factories, offices, schools, hospitals and other buildings.

The schedule of recommended values of illumination for different occupations has always been an important part of the Code. This has been extended to include many occupations not previously listed and all values of illumination have been carefull revised to bring them into line with modern requirements. A new and simpler method for estimating the illumination required for any task is given.

Of particular significance is that for the first time recommendations are made for limiting the degree of discomfort glare experienced in different occupations. Tables have been prepared which enable the probable degree of glare present in an existing or projected installation of general artificial lighting to be derived quickly and easily for comparison with the recommended value for the particular occupation. It is believed that these new data constitute a most important advance and should lead to improved quality in the design of lighting installations.

In all buildings close integration of the natural and artificial lighting systems is necessary if standards of good lighting are to be achieved at all times and this Code recommends a new approach to daylight design which recognizes that in some buildings—particularly many of modern design—use of artificial lighting to supplement daylight is called for. Appropriate recommendations are made for achieving the necessary functional requirements throughout a building while preserving the essential daytime appearance.

Other important aspects of good lighting for which new recommendations are made in the Code include the use of directional lighting to reveal form and texture, the correlation of the lighting in different areas of a building and the proper maintenance of both natural and artificial lighting systems.

Copies of the Code may be obtained from the Society's offices, price 12*s*. 6*d*. per copy.

I.E.S. Technical Report No. 2

Calculation of Coefficients of Utilization
The British Zonal Method

Technical Report No. 2 introduces an important new method of calculating coefficients of utilization. The method is simple to use and gives the practising lighting engineer a degree of accuracy and flexibility not previously possible.

Part I of the Report deals with the British Zonal Method which enables the proportion of light from an installation which falls directly on the working plane to be obtained by simple arithmetic, and the total light on the working plane to be obtained by the use of comprehensive tables designed for easy reference. Data for luminous ceilings are included. Coefficients of utilization to a high accuracy can be obtained by use of this method. Part II describes the new British Zonal Classification of lighting fittings in terms of their direct contribution to the light on the working plane. This classification is used both to simplify the determination of coefficients of utilization and as the basis for the new I.E.S. Glare Index System. Part III deals with the British Zonal Classified Method by which the coefficient of utilization is obtained by reference to tables of utilance for each B.Z. classification. These data are converted to coefficients of utilization by multiplying by upper and lower light output ratios. The same basic fitting data suffice both for the calculation of coefficients of utilization and for the determination of the I.E.S. Glare Index.

The techniques described in this Technical Report are the fruits of four years' work by the Lighting Design Data Panel of the I.E.S. Technical Committee. They represent a considerable departure from established

techniques and a considerable advance in convenience, accuracy and scope. Whilst they are sufficiently flexible to deal with the wide variety of light distributions, room dimensions and decorative treatments encountered in practice, they provide a high degree of accuracy and are easy to apply.

The B.Z. method provides a uniform basis for lighting calculations and opens the door to a general advance in lighting practice comparable with that initiated by the work of Harrison and Anderson in 1920, in so far as it makes possible, in conjunction with I.E.S. Glare Data, the integration of quantitative and qualitative factors in routine lighting practice. The publication of this Report marks the completion of one phase of the work being undertaken by the Society; it is also the beginning of a concentrated attack on the remaining uncertainties in lighting design, such as lighting depreciation, more accurate assessment of reflection factor, and, above all, luminance requirements for both comfort and pleasantness of lighting. There is good reason to look for early results from such studies, and hence to look forward to the more effective participation of lighting engineers in the art as well as the science of lighting, for true art requires not only imagination but also professional skill and knowledge to translate it into reality.

Copies of Technical Report No. 2 can be obtained from the Society's offices, price 10*s*. 6*d*. per copy.

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